Cardiovascular Parallel MR Imaging at 3.0 Tesla

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Introduction

Cardiovascular MR (CVMR) imaging has proven to be of clinical value for the assessment of cardiovascular diseases (1-5). CVMR requires speed and efficiency due to physiological motion and flow constraints which dictate the viable window of data acquisition. Consequently, the challenges and the benefits of rapid MRI are nowhere more apparent than in the field of cardiovascular MRI. To meet these challenges one must balance the competing constraints of spatial resolution, temporal resolution, scan time, image quality, contrast-to-noise ratio (CNR) and signal-to-noise ratio (SNR).

SNR improvements may be expected with the use of cardiac optimized many-element coil arrays (6,7). Even more promising in this regard is the increase in magnetic field strength available for whole-body MR scanners, which improves the baseline SNR in CVMR (8-17). This development is one of the driving forces for the broad move towards clinical 3.0 T whole body MR systems equipped with many channel technology, which hold the promise to advance the capabilities of cardiovascular MR imaging (15,16).

Parallel imaging represents an important enabling factor for comprehensive cardiac examinations at 3.0 T. The increased speed and efficiency associated with parallel MRI may be translated into extra diagnostic value for high-field CVMR in various ways, including:

- enhancing image quality
- overcoming physiological (RF power deposition, peripheral nerve stimulation, acoustic noise) and physical (gradient switching rate dB/dt) constraints,
- shortening long examinations
- improving spatial resolution and anatomic coverage and
- improving temporal resolution.

SNR losses associated with parallel imaging often constitute a practical obstacle at field strengths of 1.5 T and below. It has been predicted, however, that high field strengths, in addition to increasing the baseline SNR available for accelerated studies, may also reduce noise amplification in parallel imaging (18,19). Hence, the SNR advantage of high field applications makes parallel imaging techniques natural candidates to provide the scan accelerations required for short comprehensive cardiac MRI examinations.

In this review, some of the fundamentals of parallel imaging methods now in use for CVMR will be outlined, and examples of cardiovascular parallel MR imaging strategies at 3.0 T will be provided. Next, clinical 3.0 T CVMR applications will be surveyed, and some of the merits and limitations of 3.0 T CVMR will be considered. Lastly, current trends and future directions for accelerated high field CVMR will be discussed.

Fundamentals of Parallel Imaging

Parallel imaging seeks to circumvent the speed constraints of conventional MRI by acquiring some portion of the data *simultaneously*, rather than in a traditional sequential order. This reduces the number of serial phase encoding steps required to form an image of a given spatial resolution and field of view, which results in significant scan acceleration while still providing the full spatial information.

In particular, parallel imaging strategies use **RF detector coil sensitivities** to encode simultaneous spatial information. Each component coil in an array provides information about a distinct portion of the imaged FOV based on the spatial distribution of its sensitivity to the MR signal. Undersampled data are acquired using an array, with a reduced number of encoding gradient steps as compared with traditional unaccelerated acquisitions, and the missing information is reconstructed using knowledge of the coil

sensitivities. Three intuitive pictures are helpful to understand the undersampled acquisition and image reconstruction approaches of parallel imaging:

- **k-space picture**, exemplified by the original SMASH technique (20), which involves the regeneration of missing k-space lines corresponding to omitted phase-encoding gradients.
- **image-domain picture**, as represented by the original Cartesian SENSE formulation (21), which involves the unfolding of aliased voxels that result from undersampling.
- **generalized perspective**, which treats the encoding functions from each coil or gradient step as distinct projections of the imaged volume, and performs a generalized reconstruction from projections to generate images. This perspective has been shown to connect the SMASH-like and SENSE-like pictures (22-24).

Tradeoffs for the increased speed and efficiency afforded by parallel imaging include the need to calibrate coil sensitivity patterns, the possibility for image artifacts when calibration is inaccurate, and a reduction in SNR compared with unaccelerated imaging using the same coil array.

As an acquisition strategy rather than an imaging sequence per se, parallel imaging may be combined productively with most existing pulse sequences. However, successful cardiovascular parallel imaging requires careful selection of appropriate imaging sequences and parameters to yield the desired contrast and image quality. Certain sequences have particular advantages when combined with parallel imaging such as steady-state free precession (SSFP) techniques which offer a high intrinsic SNR. Single-shot imaging sequences tend to benefit in a particularly dramatic fashion from parallel imaging accelerations. By allowing faster acquisitions, parallel imaging limits relaxation-related signal attenuations that can degrade image quality for prolonged echo trains. For example, echo-planar imaging (EPI) sequences behave synergistically with acceleration, since time-dependent phase accumulations responsible for susceptibility artifacts are limited when echo train length is reduced. Even for multi-shot sequences, careful sequence design can result in potentially unexpected benefits. For sequences with multiple phase-encoded directions (e.g. 3D sequences), acceleration may be applied along multiple directions simultaneously, so that the net acceleration factor becomes the product of individual acceleration factors along each dimension (25).

In recent times, parallel imaging has been combined productively with techniques that use **spatiotemporal correlations in dynamic imaging**. In these techniques, the availability of multiple time frames affords one the opportunity to vary acquisition trajectories as a function of time. This is the concept behind techniques such as UNFOLD and *k-t* BLAST, all of which have been used primarily for CVMR. UNFOLD (26,27) uses temporally interleaved acquisition strategies. The k-t BLAST approach (28,29) allows a more general temporal ordering of data acquisition, and uses spatiotemporal correlations measured from training data to reassemble image components that are distributed in time and space. In all cases, spatial information from coil arrays can be combined with temporal information to yield increased net accelerations for dynamic imaging. Examples of accelerated spatio-temporal hybrid techniques include UNFOLD-SENSE, TSENSE, k-t SENSE (27,28,30).

Cardiovascular Parallel MRI Applications at 3.0 T

Imaging of cardiac anatomy and structure

Imaging of the cardiac anatomy and structure using fast spin-echo based imaging techniques benefits from the synergy between high magnetic field strengths and parallel imaging. Parallel imaging helps to limit relaxation-related blurring by allowing reduced echo train lengths for any given acquisition time. Meanwhile, high accelerated image quality is enabled by the increase in baseline SNR available at 3.0 T as opposed to 1.5 T – an SNR increase ranging from 30% in double inversion recovery (IR) prepared techniques to 75 % for triple IR fast spin-echo imaging (15) (see Figure 1). Perhaps the greatest benefit of parallel imaging for fast spin-echo imaging at high magnetic field strength is the capability to reduce the total power deposition by omitting phase encoding steps and corresponding RF refocusing pulses. The benefits of parallel imaging in this context can be

supplemented by the application of variable flip angle and hyperechoes (31-33), and otherwise rather stringent constraints on high-field pulse sequences may safely be relaxed. Of course, simple acceleration also has its benefits. For example, the use of high acceleration factors enabled by many-element coil arrays (34,35) and supported by the SNR benefits of 3.0 T promises to allow breath-held 3D black blood imaging with whole heart coverage – an approach which would eliminate the risk of slice misregistration.

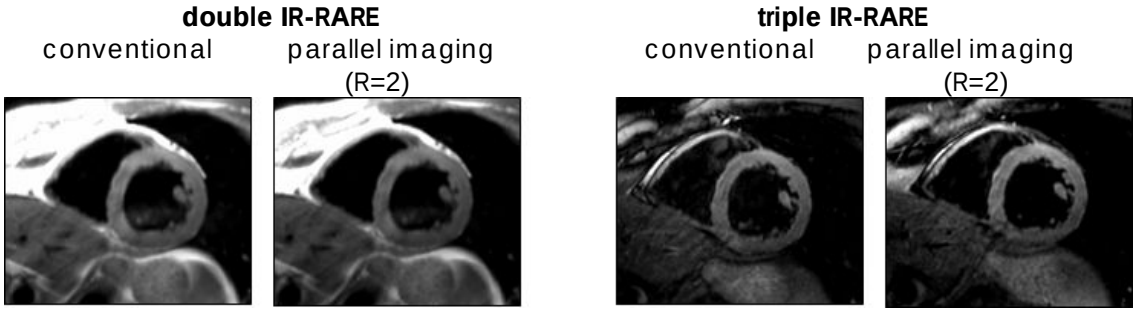

Fig. 1: Short axis views obtained from double IR-RARE **(left)** and triple IR-RARE **(right)** acquisitions using the conventional and accelerated (R=2) approach.

Assessement of global cardiac function using dynamic CINE imaging

High SNR and CNR are essential for the precise assessment of global cardiac function using CINE imaging. The linear dependence of the equilibrium magnetization on the main magnetic field strength translates into a SNR improvement for unaccelerated SSFP-based 2D CINE-imaging at 3.0T though the average SNR increase can be lower than that predicted by the theory (10,11,15) due to electrodynamic constraints. Recently, two-fold accelerated 2D CINE SSFP imaging at 3.0T (Figure 2) using cardiac coil arrays showed improved SNR and CNR performance as compared to accelerated 1.5 T acquisitions (15,36).

With 8 to 10 short axis slices required to achieve apex-to-base coverage, the conventional CINE imaging approach, which is generally confined to 1-2 slices per breath-hold, results in prolonged examination times of approximately 10 minutes. These prolonged scan durations may diminish patient comfort and compliance, and may result in appreciable slice misregistration. The 3.0 T baseline SNR advantage together with the improved efficiency of parallel acquisition strategies helps to overcome these difficulties by allowing (i) accelerated 2D CINE techniques encompassing multiple slices per breath-hold or (ii) single breath-hold whole heart coverage 3D CINE acquisitions. To achieve the high accelerations required without incurring prohibitive SNR losses, spatio-temporal correlations in dynamic CINE imaging can be exploited using the *k-t* BLAST and *k-t* SENSE approach.

One caveat about translating the 3.0 T SNR advantage into an improved spatial resolution in small FOV CINE imaging is the requirement that the target "full" field of view after parallel image reconstruction be free of aliasing along any accelerated direction. In SENSE-based imaging the overlap of structures in the target field of view leads to ambiguities in the partitioning of intensities among aliased positions resulting in image artifacts. These artifacts can be removed by using the UNFOLD approach without compromising the spatial resolution (26,27). The k-t BLAST approach also offers the potential to be free of overlapping artifacts. The effect of "full FOV" aliasing in other reconstructions such as GRAPPA is not as clear, but some relaxation of the FOV constraint has been recently reported to be possible for these reconstructions (37).

The SNR benefit demonstrated for 2D CINE imaging at 3.0 Tesla in conjunction with highly accelerated acquisition strategies also allows the capture of an increased number of cardiac phases, resulting in an improved temporal resolution without exceeding breath-hold constraints. Such approaches should allow highly accurate wall motion tracking and tracking of small rapidly moving structures such as valve cusps throughout the cardiac cycle – a capability expected to be beneficial for the examination of valvular disease.

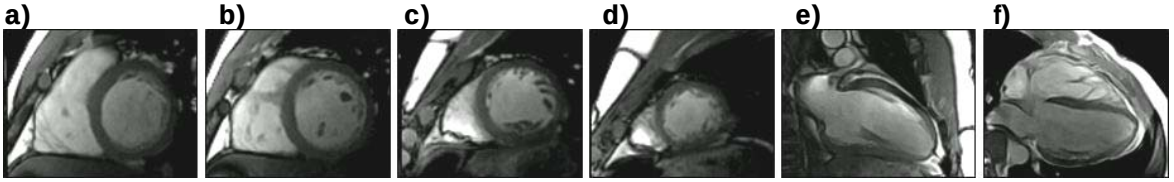

Fig. 2: Short axis views **(a-d)**, two chamber view **(e)** and four chamber view **(f)** obtained from two-fold accelerated SSFP acquisitions.

Regional myocardial wall motion tracking

Methods which track the deformation of pre-saturation tagging patterns as a function of displacement have proven to be of clinical value for the assessment of regional myocardial wall motion (38). One obstacle to myocardial tagging at 1.5 Tesla is the limited life time of the saturation tags, which can be attributed to T_1 relaxation. Consequently, the CNR between the saturation tags and surrounding myocardium is diminished during end-diastole. Recent results obtained at 3.0 T suggest that myocardial tagging techniques benefit from higher magnetic field strengths (15,16). This can be attributed somewhat to the elevated baseline SNR but primarily to the T_1-prolongation of myocardial tissue at 3.0T, which in turn translates into a significant CNR increase at end-diastole at 3.0T versus 1.5T. This improvement in CNR, in combination with parallel imaging acceleration, supports the tracking of myocardial wall motion throughout the entire R-R interval. Improved visibility and persistence of the tags also promises to improve the performance of automated contour detection for rapid and routine regional wall motion assessment (39,40).

Detection of myocardial infarction and assessment of myocardial viability

The established CVMR assessment of ischemic heart disease includes delayed contrast-enhanced imaging using ECG gated, segmented imaging modules preceded by an inversion recovery preparation to provide a consistent high contrast between infarcted and healthy myocardium (41). The resulting low SNR due to suppression of background and healthy myocardial signal presents a challenge for combinations with parallel imaging. As might be expected, this challenge can be offset by the use of high magnetic field strengths. Accelerated imaging of delayed enhancement is of clinical importance since the established unaccelerated approach, which exhibits a very limited spatial coverage of only 1 to 2 slices per breath-hold, results in prolonged examination times of 10-15 minutes with corresponding patient discomfort and decay of contrast agent concentration over the course of the exam. Parallel imaging at 3.0 T can overcome these difficulties by allowing whole-heart coverage in a single breath-hold, increasing patient comfort and ensuring uniform suppression of healthy myocardium for all imaged sections.
On the other hand, the use of standard inversion pulses can result in an inhomogeneous signal suppression of healthy myocardium, and this effect is pronounced at 3.0 T given the higher B_1-field inhomogeneity of the transmit coils currently available due to the interaction of the B_1-field with the sample/body. Recent findings demonstrate that this problem can be overcome by using an adiabatic inversion preparation pulse (15,42) though the total power deposition remains a concern (which, of course, can be addressed by reducing the number of adiabatic pulses using parallel imaging).
Meanwhile, a phase sensitive reconstruction of inversion recovery (PSIR) has been shown to enhance the contrast between healthy and infarcted myocardial tissue (43). This approach includes a T_1-weighted inversion recovery data set and an extra reference image. The latter requires 2 R-R intervals for full magnetization recovery and hence doubles the total scan time as compared to the conventional 1 R-R interval approach. This drawback can be compensated by using the time savings inherent to parallel imaging which facilitate short breath-hold times as illustrated in Figure 4.

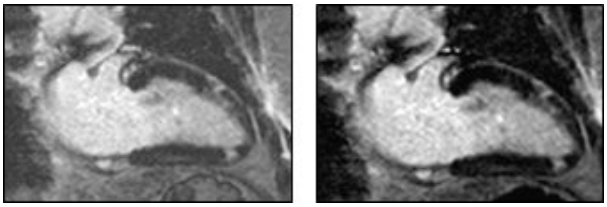

Fig. 4: Two chamber views obtained from delayed enhancement imaging. For the conventional approach **(left)** 1 R-R interval was used for recovery of the magnetization to achieve breath-hold duration of 12 sec. The PSIR approach **(right)** required 2 R-R intervals for full magnetization recovery which was compensated by using two-fold accelerated parallel imaging to keep the breath-hold time at 12 s.

First pass myocardial perfusion imaging

Rapid first-pass contrast-enhanced MRI has become a valuable tool for the assessment of myocardial perfusion using saturation-recovery-based techniques to capture contrast agent passage kinetics by achieving one- or two-heart-beat temporal resolution (44-47)**.** Remaining obstacles to a broader clinical acceptance of first-pass perfusion MRI are

- the limited in-plane spatial resolution resulting in Gibbs ringing artifacts (48) and
- the limited anatomic coverage

achievable with this temporal resolution. Substantial SNR, CNR and overall image quality improvements were reported for first-pass perfusion imaging using T_1-weighted segmented EPI at 3.0 Tesla (15,49,50). These results indicate that myocardial perfusion imaging may benefit directly from the synergy between high magnetic field strengths and parallel imaging by transferring the SNR advantage into enhanced spatial and/or temporal resolution. For this purpose, the k-t BLAST and k-t SENSE approach can be used to double the spatial coverage per unit time while preserving in-plane spatial resolution. Alternatively, k-t BLAST and k-t SENSE can be put to use to double the in-plane matrix size without impairing the temporal resolution as illustrated in Figure 3. The accelerated approach revealed an image quality superior to that of the unaccelerated approach, primarily as a result of the suppression of Gibbs ringing artifacts. High-field parallel imaging can also be exploited (i) to transition from first pass single-heart-beat multi-slice 2D acquisitions to whole heart coverage 3D acquisitions and (ii) to foster the development of arterial spin labeling based myocardial perfusion imaging (51).

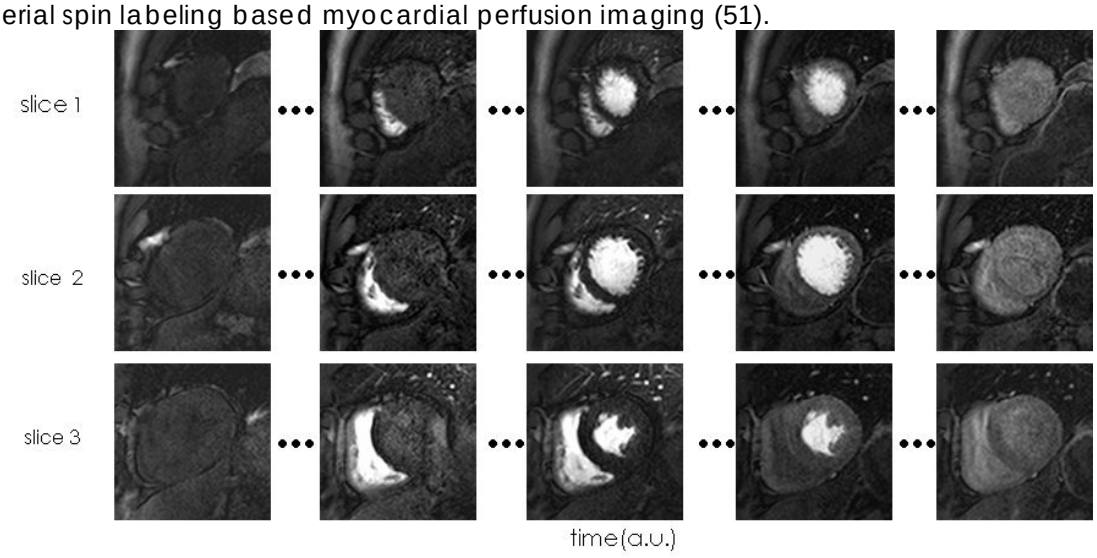

Fig. 3: Short axis views obtained from 5-fold accelerated first pass perfusion imaging using k-t BLAST, which facilitated a matrix size of 192x192 while preserving the 1 R-R interval temporal resolution.

Coronary MR angiography (CMRA)

CMRA at 3.0 T remains technically challenging due to SAR constraints, off-resonance effects and susceptibility artifacts (52,53) though baseline SNR improvements inherent to higher magnetic field strengths have been demonstrated (9). Parallel imaging strategies provide several means of improving CMRA image quality by minimizing the impact

physiological motion (54,55) and by permitting an improvement in the spatial resolution and anatomic coverage (55,56), while maintaining appropriate limits on RF power deposition.

One study of accelerated free breathing 3D navigated coronary MR angiography at 3.0 T showed that the geometry-dependent noise amplification factor g remained close to the optimal value of one for an acceleration factor of R=2 (56). Image quality derived from gradient echo based free breathing 3D navigated imaging was competitive with that obtained from unaccelerated imaging using identical parameters. The time savings associated with parallel imaging can be also translated into an improvement of the in-plane and through-plane spatial resolution, which resulted in an improved delineation of proximal and, most especially, distal segments of the coronary arteries (56).

In another study, the feasibility of rapid breath-held CMRA at 3.0 T was demonstrated by combining parallel imaging with 3D SSFP (54)**.** In this study, volume selective shimming was used to offset susceptibility effects and the flip angle of the excitation pulse was adjusted to permit appropriate contrast between the blood pool and the surrounding myocardium (see Figure 5) without exceeding SAR-limits or impairing the image quality due to off-resonance effects or susceptibility artifacts. High SNR breath-held CMRA at 3 Tesla was completed in 2-3 breath-holds covering the main branches of the coronary arterial systems. This initial 3.0T experience suggests that the SNR improvement coupled with the enhanced CNR between the blood pool and the myocardium may provide benefits for clinical coronary MR angiography.

For either free-breathing or breath-hold approaches, conventional CMRA studies are generally restricted to targeted thin slabs encompassing a particular segment of the coronary artery tree only. Parallel imaging allows the use of a thicker volume, which supports the visualization of long tortuous segments of the coronary arteries and offers the potential to eliminate localization scans (6,57). As larger acceleration factors are explored with many-channel MR systems, the benefits of high field strengths for CAI will become even more pronounced through an increase in the volume coverage which may permit the visualization of the entire coronary tree within a single breath hold (6,57) or a 1-2 min navigator corrected free breathing acquisition (53,58).

The T_1 prolongation and SNR gain together with the speed benefit of parallel imaging will also prove to be useful for flow targeted imaging of the coronaries at 3.0 T. Even more, the SNR improvements not only promise to be beneficial for MR lumography but also for vessel wall imaging (59). As high spatial resolution vessel wall imaging is accomplished at 3.0 T intrinsic contrast mechanisms and specific contrast agents can be used for plaque detection and plaque characterization supported by the use of targeted contrast agents.

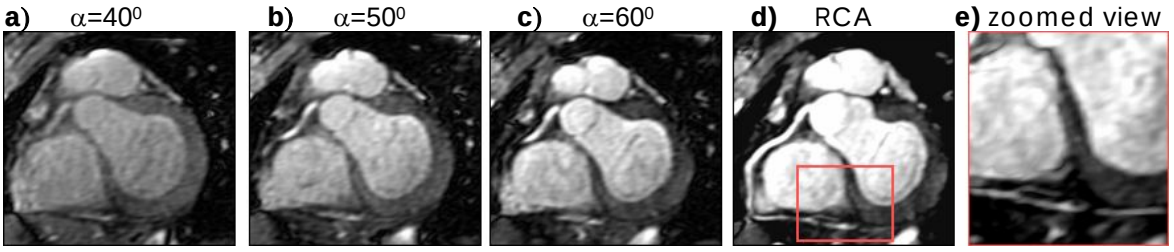

Fig. 5: Single slice views (a-c) and maximum intensity projections **(d,e)** of the right coronary artery (RCA) using two-fold accelerated short breath-hold ECG gated, fat-saturated 3D SSFP to reduce the sensitivity to cardiac motion by shortening the acquisition window length within the cardiac cycle.

Vascular imaging

The conventional first pass MRA approach is based on contrast enhancement due to the injection of contrast media (3,60). The comparatively short time intervals associated with the passage of contrast agents through the vascular system require rapid imaging techniques for continuous bolus tracking or appropriately timed bolus chasing (61). Hence, high speed contrast enhanced MRA is a particularly appealing candidate for parallel imaging. Both the 3.0 T SNR advantage and the imaging speed gain associated

with parallel MRI may be invested to improve temporal resolution in time-resolved MRA down to 1 ms in order to clearly distinguish arterial from venous phases or to evaluate contrast dynamics while achieving comparatively large volume coverage (35,62). Alternatively, parallel imaging may be used to improve anatomic coverage or spatial resolution in a given imaging time (35,63). MRA approaches that do require synchronization with the cardiac cycle also stand to benefit from parallel imaging at high field strengths due to the substantial reduction in motion artifacts without exceeding scan time requirements for breath-held acquisitions.

Current Trends and Future Directions

Comprehensive cardiovascular MR imaging at 3.0 Tesla appears to be feasible for the assessment of cardiac morphology and function. Though the management of SAR limitations and susceptibility effects is expected to remain a primary concern, the extra diagnostic value afforded by the SNR and CNR advantages at 3.0 Tesla will clearly pave the way for further developments in this area including improvements in the B_1-homogeneity using adiabatic RF pulses (15,42) or transmit SENSE approaches (64,65).

The need for speed together with the baseline SNR benefit obtained at 3.0 Tesla will motivate further advances in applying parallel imaging in routine cardiovascular MR while preserving or improving the image quality achieved at 1.5 Tesla. Access to massive accelerations afforded by the synergy between many element coil arrays and high magnetic field strengths would serve to further enhance immunity to physiological motion by allowing even shorter acquisition windows. Higher acceleration factors would also afford more robust segmented acquisition schemes, which are suitable for very high heart rates and hence might facilitate pharmacological stress applications in the near future.

Highly parallel imaging strategies are also appealing for the pursuit of whole heart coverage in acceptable breath-hold times. As larger acceleration factors are examined clinically with many-channel MR systems (6,35), the benefits of high field strengths for whole heart coverage applications will become even more pronounced. Meanwhile, parallel imaging can help to address some of the practical limitations of high-field MRI, including susceptibility artifacts, acoustic noise and RF power deposition. Thus, there is a powerful potential synergy between high-field MRI and parallel imaging which remains to be further explored.

The speed advantage and extra diagnostic value afforded by parallel imaging at 3.0 T may be expected to drive future technological developments. One development that is already underway is a broad move towards commercial 3.0 T MR systems with 32 or more receiver channels. The practical design and operational requirements of many-element cardiac optimized coil arrays operating at 127 MHz are also likely to motivate further advances in conductor arrangement, cabling methods, substrate material, and image reconstruction software and hardware.

All of these developments promise to further advance the spectrum of clinical cardiovascular MR applications such as vessel wall imaging and plaque characterization. As routine comprehensive cardiovascular MRI is accomplished at 3.0 Tesla, the merits of otherwise unattainable SNR paralleled by acquisition speed improvements not only promise to be beneficial for coronary artery and large cardiac vessel visualization but will also prove to be useful for the assessment of the cardiac function, myocardial perfusion, blood flow and myocardial viability for the detection of heart disease.

In conclusion, the capacity for rapid imaging enabled by high magnetic field strengths, many-channel MR systems and highly parallel MRI promise to translate MR physics and technology into extra diagnostic value not only by streamlining cardiovascular MRI for structural and functional imaging but also by facilitating targeted tissue characterization through parametric mapping and by opening a broader access to physiologic and metabolic information.

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